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Supplement 6

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APOLLO 9 MISSION REPORT

PERFORMANCE OF THE LUNAR MODULE REACTION CONTROL SYSTEM

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MANNED SPACECRAFT CENTER
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PERFORMANCE OF THE LM RCS DURING THE AS-504/SC-104/LM-3 MISSION (APOLLO 9)

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PREFACE

This report has been prepared as supplement 6 to the Apollo 9 Mission Report (MSC-PA-R-69-2).

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ABBREVIATIONS

AGS	abort guidance system
AOT	alignment optical telescope
APS	ascent propulsion system
ASC	ascent
CDH	constant delta height
CES	Control Electronics Section
CSI	coelliptic sequence initiation
CSM	command and service module
CW	caution and warning
DPS	descent propulsion system
DTO	detailed test objective
e.s.t.	eastern standard time
EVA	extravehicular activity
GAEC	Grumman Aircraft Engineering Corporation
g.e.t.	ground elapsed time
G.m.t.	Greenwich mean time
IMU	inertial measurement unit
KSC	Kennedy Space Center
LM	lunar module
LMP	lunar module pilot
MSOV	main shutoff valve
O/F	oxidizer to fuel
oxid	oxidizer

PGNCS	primary guidance and navigation control system
PIPA	pulse integrating pendulous accelerometer
PIT	preinstallation test
P/N	part number
PQMD	propellant quantity measuring device
PVT	pressure-volume-temperature
RCS	reaction control system
RR	rendezvous radar
RSS	root sum square
S-IVB	Saturn IVB
SLA	spacecraft/LM adapter
SPS	service propulsion system
TCA	thrust chamber assembly
TCP	thrust chamber pressure
TM	telemetry
TMC	The Marquardt Corporation
TPI	terminal phase initiation
ΔV	change in velocity

PERFORMANCE OF THE LM RCS DURING THE AS-504/SC-104/LM-3 MISSION (APOLLO 9)

By Donald R. Blevins, Bernard J. Rosenbaum,
and Lonnie W. Jenkins

SUMMARY

The Apollo 9 vehicle was launched from John F. Kennedy Space Center (KSC) Launch Complex 39A at 16:00:00.7 Greenwich mean time (G.m.t.) on March 3, 1969. The command module landed in the Atlantic at 17:00:54 G.m.t. on March 13, 1969. Apollo 9 was an earth orbital mission.

The lunar module (LM) reaction control system (RCS) performed satisfactorily throughout the mission. The only problem noted was a "failed on" thrust chamber pressure (TCP) switch which was used to monitor the quad 4 upfiring engine (B4U). All test objectives were satisfied.

A significant decrease in the natural frequency of the LM RCS fuel and oxidizer manifold pressure fluctuations was noted during interconnect feed operations associated with the ascent propulsion system (APS) burn to depletion. This decrease was apparently caused by either free helium which entered the RCS manifolds from the APS or a higher saturation level of APS propellants relative to RCS propellants. In any event, the condition was not detrimental to RCS operation.

The limited amount of spacecraft velocity data which was available indicated that RCS engine performance was nominal. In addition, the crew reported that engine performance was nominal throughout the mission. It is estimated that the RCS engines accumulated a total of 1250 seconds "on" time and 20 000 firings during the mission.

The thermal performance of the RCS was satisfactory, although the caution and warning (CW) upper quad temperature limit of 190° F was exceeded during four periods. The high temperature conditions resulted from periods of high engine activity and were not the result of any heater problems. As had been expected, no problems resulted from the high temperatures. The quad temperature measurement range will be increased on subsequent LM vehicles, and the CW range will be increased on LM-4 and deleted on LM-5 and subsequent LM vehicles.

The total propellant consumption from the RCS tanks was 353 pounds as measured by the onboard propellant quantity measuring devices (PQMD) or 369 pounds as measured by a ground-calculated pressure-volume-temperature (PVT) analysis. The PQMD value is probably more accurate since the PQMD measured the actual helium tank temperature and the PVT analysis utilized the telemetered fuel tank temperature. An additional 99 pounds were used from the APS tanks during interconnect feed operations associated with the coelliptic sequence initiation (CSI) (staging) and APS burn-to-depletion maneuvers. Slight PQMD overshoots were noted following periods of rapid propellant usage; the maximum overshoot was about 5 pounds on a single system.

Pressure switch operation, with the exception of the switch monitoring the quad 4 upfiring engine, was nominal. The 4-up switch failed in the closed position on the first firing of the 4-up engine at 48:04:37 g.e.t. and remained closed until 98:33:33 g.e.t. when it reopened and began operating intermittently. The switch eventually returned to completely normal operation. The most probable cause of the switch failure was particulate contamination. The switch failure in no way affected the mission. The only possible effect was that the CW system would have been unable to detect a 4-up engine off-failure.

INTRODUCTION

Apollo 9 was the third manned Apollo mission, the second manned Saturn V launch, the second Apollo mission to include the LM, and the first manned LM mission. Lift-off occurred at 16:00:00.7 G.m.t. on March 3, 1969, and splashdown occurred in the Atlantic at 17:00:54 G.m.t. on March 13, 1969. The earth orbital mission covered a period of 241:00:54 hours. The crewmembers were James McDivitt, commander; David Scott, command module pilot; and Russell Schweickart, lunar module pilot.

The mission was a D-type mission with objectives as defined in Revision 1, Change A of the Mission Requirement Document, "D-Type Mission, LM Evaluation and Combined Operations." The overall objective of the mission was to evaluate LM systems performance and functional capability and to perform selected command and service module/lunar module (CSM/LM) operations (rendezvous and docking). Detailed test objectives (DTO's) involving the LM RCS were as follows:

1. P11.7 — PGNCS Attitude/Translation Control — Verify the capability of performing control functions while operating the LM PGNCS and obtain RCS propellant usage data.

2. P12.3 — AGS/CES Altitude/Translation Control — Verify the capability of performing control functions while operating the LM/AGS/CES and obtain RCS propellant usage data.

3. P16.19 — Rendezvous Radar/RCS Plume Impingement/Corona Effect — Determine the rendezvous radar (RR) high-power multiplier corona susceptibility because of RCS plume impingement on the RR antenna.

4. M17.17 — LM Environment and Propulsion Thermal Effects — Verify the performance of the passive thermal subsystem to provide adequate thermal control when the spacecraft is exposed to the natural and propulsion-induced thermal environments.

5. Obtain RCS propellant consumption during the following DTO's:

   a. P11.5 — LM IMU Inflight Alignment

   b. P11.14 — PGNCS Controlled APS Burn

   c. P20.21 — LM Evaluation Rendezvous

   d. P20.28 — LM Active Docking

The Apollo Mission D plan consisted of six periods of activities. A summary of the major spacecraft events in each of the activity periods is as follows:

1. First period — Launch, pretranslunar injection procedure exercise, transposition and docking, CSM/LM ejection, one docked service propulsion system (SPS) burn, and S-IVB unmanned restart(s)

2. Second period — Three docked SPS burns

3. Third period — LM systems evaluation, docked descent propulsion system (DPS) burn, and docked SPS burn

4. Fourth period — Extravehicular activity (EVA)

5. Fifth period — LM active rendezvous and unmanned APS long-duration burn to depletion

6. Sixth period — CSM solo activities, including two SPS orbit-shaping burns, and a deorbit burn and an Atlantic recovery-area landing

The LM RCS was not pressurized and telemetry data were not available until early in the third period. The RCS data were available during the LM powered up phases of the third, fourth, and fifth periods until the depletion of the LM battery power near the end of the fifth period.

FLIGHT PERFORMANCE

System Configuration

A LM-3 RCS simplified schematic and complete mechanical schematic are shown in figures 1 and 2, respectively. Figure 3 illustrates the location of the RCS components relative to the LM structure. Figures 4 and 5 are illustrations of the RCS thrust chamber assembly (engine) and the thrust chamber assembly cluster (quad). Table I includes the specification numbers and manufacturers of the major LM RCS components. Changes in the LM-3 configuration from the LM-1 configuration were as follows:

1. The thrust chamber pressure transducers (TMC P/N 228658) were replaced with thrust chamber pressure switches (LSC 310-651).

2. Engine-inlet pressure transducers (LSC 310-121) were not included on LM-3.

3. The in-line propellant filters (LSC 310-125) were placed upstream of the cluster isolation valves (LSC 310-403).

4. An ascent interconnect package including a primary and secondary valve (LSC 310-403) on each propellant manifold (A fuel, A oxid, B fuel, and B oxid) replaced the LM-1 configuration which included a single valve per manifold.

5. Minor line configuration changes were made in the tankage modules and propellant manifolds.

The only planned change from the LM-3 configuration for LM-4 and subsequent vehicles is the thrust chamber pressure switches which will be changed as shown in table II.

Instrumentation

The LM-3 RCS measurement list is included in table III; figure 2 illustrates the locations of the various measurements in the system. All RCS instrumentation operated normally throughout the mission with the exception of the B4U TCP switch. The B4U TCP switch failed closed on the first firing of that engine at 48:04:36 g.e.t. and remained closed until 98:33:37 g.e.t. when it started operating intermittently. The switch failure had no effect on the mission. A complete discussion of the switch failure is included in the "Thrust Chamber Pressure Switches" section of this report.

Caution and Warning System

The RCS measurements monitored by the CW and their associated trip limits are included in table IV. The ability of the CW to accurately monitor the RCS measurements was demonstrated during Apollo 9; all RCS-related CW operations were nominal. The reader should note that the TCP switches are considered to be part of the RCS and not the CW. The upper quad temperature limit of 190° F was exceeded during four occasions:

1. On quads 1 and 3 following DPS-1 (49:47:32 g.e.t.)

2. On quads 1, 3, and 4 following staging (96:20:26 g.e.t.)

3. On all quads during the terminal phase of rendezvous until after docking (98:33:23 g.e.t.)

4. On quads 1, 2, and 3 after the APS burn to depletion (102:01:30 g.e.t.)

Telemetry data (GL 4069X, master alarm on) verified the CW indications at the times shown in parentheses for occasions 1, 2, and 3, but the data were insufficient to verify occasion 4.

The CW upper limit was intended to indicate a failed "on" heater condition and was not intended to indicate high engine firing activity, which was the situation in each of the four cases mentioned. The cooling effect of propellant flow prevents overheating of the injector valves during engine activity. No problems occurred during the mission from the high cluster temperature conditions or the associated CW indications. Recent engine vendor test data indicated that the engine injector valves can withstand temperatures in excess of the maximum which could be produced by a failed "on" heater. As a result, the quad temperature telemetry range and CW limits will be increased on LM-4. The LM-5 and subsequent vehicles will include an increased measurement range, but the CW signal will be deleted entirely.

Preflight Activity

The LM-3 RCS propellant tanks and propellant manifolds were loaded in the following sequence to the values shown in table V.

1. The RCS manifolds were evacuated and the cluster isolation valves were closed at 0230 hours eastern standard time (e.s.t.) February 1, 1969.

2. The RCS fuel and oxidizer tanks were loaded on February 4 and February 8, 1969, respectively. Nominal ullages were drawn and a blanket pressure of about 50 psia was set.

3. The primary and secondary interconnect valves were opened to fill the manifolds from the APS interface down to the isolation valves; the secondary interconnect valves were then reclosed. The main shutoff valves were opened at 2000 hours e.s.t. on February 23, 1969.

4. The isolation valves were opened to fill the manifolds to the engine valves at 2000 hours e.s.t. on February 26, 1969.

Both the primary and secondary interconnect valves were closed during the manifold evacuation process; consequently, gas was probably injected into the RCS manifolds during manifold-filling operations.

Helium loading was completed at about 2000 hours e.s.t. on February 24, 1969. The helium pressures were 2988 psia at 70.2° F and 2947 psia at 69° F on system A and system B, respectively. The nominal pressure is 3050 psia at 70° F (1.03 lbm of helium), and the PQMD calibrations were based on a nominal load. Therefore, the PQMD indications were slightly lower than normal throughout the mission.

Table VI is a summary of the preflight system pressure histories. As shown in the table, the propellant manifolds maintained the same vacuum pressure for 22 days. The gradual increase in regulator outlet pressure during the prelaunch period was within the allowable check-valve reverse-leakage limits. All prelaunch helium and propellant manifold pressures were nominal.

Flight Time Line

Table VII contains a list of the major mission events and activities pertinent to the LM RCS.

Helium Pressurization System

The helium pressurization system performance was nominal throughout the mission. The helium squib valves were actuated at 47:36:58 g.e.t. to pressurize the RCS propellant tanks and manifolds to operating pressure. Following squib actuation, the propellant manifold pressures increased very smoothly at a rate of approximately 70 psi/sec; no pressure overshoots were observed. Operating pressure was reached in all manifolds in about 2 seconds. The regulators maintained acceptable outlet pressure (between 178 and 184 psia) throughout the mission. No evidence of external leakage was observed.

Figure 6 is a comparison of the system A and system B helium tank pressures and PQMD outputs for the portions of the mission which required LM RCS operation. The close relationships between tank pressure and PQMD output is evident from the figure. As the result of helium cooling, the helium tank pressures and the PQMD's overshot following periods of rapid propellant consumption. The overshoots ranged as high as 55 psi and 1.8 percent (5 pounds of propellant) on the tank pressures and PQMD's, respectively.

Propellant System

The propellant supply system functioned normally throughout the mission. No evidence of propellant leakage was noted.

The crew reported that when the ascent FEED 2 switch on system A (fig. 2) was placed in the "closed" position to verify that the secondary interconnect valves were closed before RCS pressurization, one system A talkback read gray for approximately 20 seconds. Flight data indicated that the valve position indicators operated properly; therefore, the talkback was "sticky." The "sticky" talkback persisted on subsequent system A ASC FEED 2 commands, but had no effect on the mission.

Shortly after RCS pressurization, the system A secondary interconnect valves were inadvertently opened for about 3.3 seconds (from 47:39:35.1 to 47:39:38.4 g.e.t.). This allowed about 5 pounds of RCS propellant to transfer into the APS, which was then pressurized at 150 psia. The inadvertent opening occurred during a procedure to verify that the secondary interconnect valves were closed and the primary interconnect valves were open following RCS pressurization. The system A main shutoff valves (MSOV) remained open during this period. No resultant problems were noted.

Manifold pressures throughout the mission remained within the normal RCS range except for the two scheduled periods of APS interconnect operation. During interconnect operation, the manifold pressures increased to the nominal 186-psia APS pressure, except during the APS burn to depletion when the manifold pressures decreased to 167 psia as the result of an APS regulator problem. Both RCS systems were scheduled for transfer to the interconnect mode during the final LM cabin closeout, but only system B was transferred (100:49 g.e.t.). System A remained in the normal feed mode throughout the remainder of the mission.

The crew reported that both the system A and system B primary interconnect valves (ASC FEED 1) produced an audible indication of a position change when they were energized "open" to verify that they were in the open position following APS pressurization. This would indicate that the primary interconnects had closed sometime between RCS pressurization and the audible indication. Available data are insufficient to determine if the valves had actually "shuttled" closed. It is possible that the valves were closed following the inadvertent system A interconnect valve opening noted previously. The incident had no effect on the mission.

A significant shift in the natural frequency of the system B fuel and oxidizer manifold pressure fluctuations occurred during firings associated with the APS burn to depletion (fig. 7). The natural frequency of the fuel manifold was 18 Hz prior to the ullage burn, gradually decreased to 9 Hz during the first 15 seconds of the ullage burn, and remained at 9 Hz throughout both the remaining ullage burn (34.1-second firing) and the APS burn. The fuel frequency immediately increased to about 14 Hz after the APS engine cut-off. The oxidizer natural frequency was about 9 Hz prior to the ullage burn, decreased to about 8 Hz during the ullage firing, and gradually decreased to 7 Hz during the APS burn. The oxidizer frequency also immediately increased to 14 Hz at APS engine cut-off. The initial decrease in natural frequency could have been caused by one or more of the following:

1. Helium ingestion from the APS as the result of opening the interconnect valves without first performing an ullage burn to settle the propellants.

2. The APS propellants saturated to a higher percentage and at a higher pressure than the RCS propellants could result in a frequency change without the generation of free gas bubbles in the system.

3. The ullage acceleration forcing possible free, minute helium bubbles suspended within the propellants to accumulate in "high points" of the manifold, consequently changing the effective manifold length.

The first explanation appears most probable. Rough calculations indicate that a two-engine ullage firing would require about 6 and 8 seconds to carry a helium bubble from the APS tank outlet to the RCS oxidizer and fuel manifolds, respectively, assuming the bubble moved with the propellant. On the other hand, neither the APS chamber pressure nor the RCS pressure switches provided any indication of free gas passing through the engine. The pressure switches, however, are generally insensitive to ingested gas. The second possible cause must also be considered, primarily because of the uncertainty in determining the time required for the helium to saturate the propellants. Assuming that both the RCS and APS propellants were saturated at their respective nominal manifold pressure (180 and 186 psia), calculations indicate that the small additional helium dissolved in the APS propellants was insufficient to account for the frequency shift. On the other hand, if the APS propellants were saturated and the RCS propellants were not, as could be the case because of the much higher APS pad pressure (150 psia versus 30 to 50 psia for the RCS), calculations indicate that the more saturated APS propellants (lower natural frequency) would definitely decrease the frequency. A lack of base-line data precludes calculation of the specific decrease.

The sudden step increase in natural frequency after APS engine cutoff was apparently caused by a large slug of APS helium entering the RCS lines. Calculations show that RCS propellant usage after APS propellant depletion exceeded that amount contained within the manifold segment leading from the APS to the RCS, thus helium was forced into the RCS lines. Because the interconnect valves are located roughly in the middle of the RCS manifold, the helium bubble in effect decreased the effective manifold lengths by about a factor of two, consequently increasing the natural frequency. The existence of a helium bubble within the manifold at this time was corroborated by the pressure fluctuations associated with engine firings. The manifold transducers were relatively insensitive to firings of engines located on one side of the transducer but were responsive to firings of engines located on the other side of the transducer.

Engine Performance

Engine performance was reported by the crew as nominal throughout the mission. Specific postflight performance data were quite limited; however, the available data contained no indication of other than nominal operation.

Accurate performance data were available for only the downfiring engines, and during only the CSI (staging) maneuver and the ullage burn for the APS burn to depletion. All other engine performance data were either missed because of operation between stations or were available as only rather dispersed maximum and minimum thrust values. No accurate performance data were available from the attitude control firings because of the combination of low sample rate, short pulse widths, and rate gyro insensitivity.

The calculated performance values are summarized in table VIII. The ΔV expected values were based on the summation of the engine on-times corrected for attitude control firings and the engine effective thrust corrected for predicted plume impingement losses. The ΔV actual data were simply the summation of the computer word pulse integrating pendulous accelerometer (PIPA) counts converted to feet per second. The "average effective thrust" values were calculated by using the vehicle mass, the indicated ΔV (computer word PIPA counts), and the engine ontimes.

The data in table VIII are presented as a maximum and a minimum effective thrust. This was necessary because the ΔV data (PIPA counts) are telemetered once every 2 seconds in whole numbers only. The PIPA registers are then zeroed, thus any fractional counts are lost. The minimum thrust values were calculated assuming that the lost fractional counts were zero, whereas the maximum values assumed the loss was 0.9999 count per 2 seconds. As a result, an actual check against the predicted thrust loss of down-engine firings with the unstaged vehicle was not available. The loss, because of plume impingement on the descent stage, was predicted to be 8 pounds for engines 1-, 3-, and 4-down and 37 pounds for engine 2-down (the additional loss was the result of an added shelf on the descent stage below engine 2-down).

The lack of complete data coverage plus the occasional noise in the available jet-driver bilevels made it impossible to determine exact values for total firing time and total number of firings. However, a rough estimate of the total burn time is 1250 seconds based on total propellant consumed. The estimated number of pulses is 20 000 based on an assumed 50-millisecond average pulse width exclusive of steady-state firings.

Thermal Control

The thermal performance of the RCS was satisfactory, although the CW upper quad temperature limit of 190° F was exceeded during the four occasions listed in the "Caution and Warning System" section of this report.

The CW upper temperature limit was selected to identify a failed-on heater condition and was not intended to indicate high engine firing activity, which was the situation in each of the four cases. As expected, no problems resulted from the high temperatures. Examples of quad and engine component temperature profiles during several portions of the mission are shown in figure 8. This figure illustrates that the engine injector valve temperatures decreased rapidly during periods of high engine activity because of the cooling effect of propellant flow. By the time the injector valves returned to their nominal temperatures, the quad temperatures had cooled to below the upper CW limit. Unfortunately, the component temperatures were not available during the final stages of rendezvous and docking when the quad 4 temperature remained above the CW upper limit for a sustained period of time (1 hour and 20 minutes). Figure 8 also illustrates that down-engine firings had the greatest influence on quad temperatures.

When the engine heaters were active, the quad temperatures ranged from 139° F (the lower CW limit was 117° F) to above 209° F during periods of high engine activity. The maximum temperature was beyond the telemetry instrumentation range. When the engine heaters were not active, (for example, during the EVA period) quad temperatures ranged from 63° to 101° F, well above the freezing points of the propellants (18° to 21° F for the fuel and 12° F for the oxidizer). Unfortunately, the exact quad warmup time (time from heater activation to steady-state temperature) was not available because of limited station coverage. However, it could be determined that the warmup time was 30 minutes or less on all quads during both the first and second heater activations. The RCS fuel tank temperatures ranged from 66° to 70° F. The quad temperatures during the mission are shown in figures 9 and 10.

Propellant Utilization and Quantity Gaging

A comparison of the total RCS propellant consumption profile with the flight plan predicted profile is included in figure 11. The propellant consumption was measured by the onboard PQMD's and a postflight ground calculated PVT analysis. Results of the PVT analysis and data from the PQMD were in close agreement during all phases of the mission. The PVT analysis was based on an oxidizer-to-fuel mixture ratio of 1.92 and the telemetered helium tank pressures and fuel tank temperatures. Both the PQMD and PVT measurements were subject to overshoot resulting from rapid helium cooling during periods of high propellant usage. The PVT analysis overshoot was more pronounced than the PQMD overshoot since it was based on a less sensitive temperature measurement (fuel tank temperature). Therefore, the PQMD results should be more accurate during and immediately following periods of high propellant usage. The PQMD and PVT overshoots are evident in figures 11 and 12. Figure 6 illustrates the relationship between helium tank pressure and PQMD output. As previously noted, the maximum PQMD overshoot was about 5 pounds on a single system.

Figure 12 includes individual system propellant consumption profiles as determined by both the postflight PVT analysis and the onboard PQMD. The maximum imbalance between system A and system B usage during rendezvous and docking was about 30 pounds following LM staging, with system B having the greater usage. This was primarily the result of the ullage burns for descent propulsion system-1 (DPS-1), DPS phasing, and DPS insertion which utilized system B propellant exclusively. A 25- to 30-pound differential was maintained between DPS insertion and the final stages of docking. At the completion of docking, the system B usage was only about 5 pounds greater than the system A usage.

System A was used in the normal mode instead of the planned interconnect mode during the APS burn to depletion. This resulted in an additional usage from system A of about 80 pounds.

Table IX is a summary of the LM RCS propellant loaded, consumed, and remaining. Table X is a breakdown of RCS propellant consumption associated with the major mission events. The propellant consumption through final docking, using the PVT analysis, was 286 pounds or 28 percent less than the predicted 400 pounds. The prediction error appeared to be primarily the result of excessive allowance for attitude control between major burns and for nulling of the ΔV residuals following major burns.

Thrust Chamber Pressure Switches

As part of the LM failure detection system, a thrust chamber pressure switch is incorporated into each RCS engine as a means of detecting a failed-off engine condition. The switch, normally open, is actuated closed by the pressurized chamber gases during engine operation. At each firing, failure detection logic compares the jet-driver firing command with the switch position signal as shown in table IV. A section drawing of the pressure switch is shown in figure 13.

Pressure switch operation, with the exception of that monitoring the 4-up engine, was nominal throughout the mission. Typically, the switches were indicated closed within 10 ± 5 msec after the jet-driver "on" indication, and reopened within 50 msec after the jet-driver "off" indication. These actuation times agree with the operating characteristics observed in ground tests.

The 4-up pressure switch, closing normally for the first firing of the 4-up engine at 48:04:37 g.e.t. apparently remained failed closed until 98:33:33 g.e.t. when it reopened and began operating intermittently. This intermittent operation continued for about 40 minutes, with the switch occasionally remaining closed after a firing for up to 40 seconds. In general, however, the switch remained closed for 5 to 10 seconds after a firing and occasionally operated normally. Normal switch operation subsequently returned and continued for the remainder of the mission. Vehicle rates and propellant consumption during the period of the failed-on switch indication were normal, thereby ruling out the possibility that the failed-on switch was indicative of a failed-on engine. Furthermore, normal operation of the 4-up engine was confirmed by visual observation by the crew. The switch failure in no way affected the mission. The only possible effect was that the CW system would have been unable to detect a 4-up engine failed-off condition.

The exact cause of the stuck-closed failure cannot be ascertained. The initial "stuck-closed" condition most likely was due to particulate contamination, whereas the cause of the subsequent "sticking" operation is not known. Particulate contamination is considered the most likely cause of the initial failed-closed condition because a small particle (4 to 6 mils) could have easily fallen into the upfiring engine during vehicle checkout. During subsequent vibrations, the particle could have moved into the pressure switch sensing port. Pressurization gases from the first firing deflected the switch diaphragm the full 6 to 8 mils displacement and at the same time could have forced the particulate matter into the switch beween the diaphragm and lower diaphragm support. The diaphragm total deflection is only 6 to 8 mils, with only 4 to 6 mils deflection required to close the switch.

CONCLUSIONS

The LM RCS performance was satisfactory during the Apollo 9 mission, and the system demonstrated the capability to perform the necessary functions for deep space and lunar orbit operations. The only hardware problem noted was the "closed" failure of the thrust chamber pressure switch which monitored the quad 4 upfiring engine. Numerous CW signals occurred as the result of exceeding the quad temperature upper limit of 190° F. Because of the engine valve cooling effect during propellant flow associated with engine firings and recent vendor test data which indicates a higher allowable valve seat temperature, the LM-4 quad temperature measurement range and CW limits will be increased. The LM-5 and subsequent vehicles will include an increased measurement range, but the CW signal will be deleted entirely.

TABLE I.- MAJOR LM RCS COMPONENTS

Description	GAEC SPEC no.	Manufacturer
Helium tank (2)	LSC 310-301	Airite
Helium squib valve (4)	LSC 310-302	Pelmec
Helium filter (2)	LSC 310-303	Vacco
Helium regulator (2)	LSC 310-305	Fairchild
Check valve (4)	LSC 310-306	Accessory Products
Relief valve (4)	LSC 310-307	Calmec
Propellant tank (4)	LSC 310-405	Bell
Main shutoff valve (4)	LSC 310-403	Parker
Ascent interconnect valve (8)	LSC 310-403	Parker
Crossfeed valve (2)	LSC 310-403	Parker
Cluster isolation valve (16)	LSC 310-403	Parker
Propellant in line filter (16)	LSC 310-125	Wintec
Thruster heater (32)	LSC 310-601	Cox
Thrust chamber pressure switch (16)	LSC 310-651	Fairchild
Engine (16)	LSC 310-130	Marquardt

TABLE II.- PRESSURE SWITCH CONFIGURATION SCHEDULE

Part number	Effectivity	Changes cumulative
LSC 310-651-5	Basic design	Backup for Belleville washer added.
LSC 310-651-5-1	LM-2 to LM-5 PA-1, 5 only	Teflon sleeve added to pigtail.
LSC 310-651-5-2	PA-1, 11 only	Electron beam welded closure hole and diaphragm.
LSC 310-651-5-3	LM-6	Diaphragm weld aged. Thermal cycled and pressurization tested at GAEC.
LSC 310-651-5-4	LM-7	Hole drilled in cover to facilitate potting and inspection of weld.
LSC 310-651-5-5	LM-3, 2 only, LM-8 and subs	Thermal cycled and pressurization tested at the vendor during acceptance test. Only PIT tested at GAEC.

Note: See figure 13 for section drawing of switch.

TABLE III.- LUNAR MODULE RCS MEASUREMENT LIST

Measurement no.	Description	Telemetry data						Onboard display				Operational	DFI
		Low	High	Units	Sample rate, Hz	Type recording	RSS accuracy, percent	Low	High	Units	RSS accuracy, percent		
GR1085Q	Prop A quantity	0	100	percent	1/1	L/H	4.0	0	100	percent	4.5	X	
GR1095Q	Prop B quantity	0	100	percent	1/1	L/H	4.0	0	100	percent	4.5	X	
GR1101P	A He tank press	0	3500	psia	1/1	L/H	2.0	0	4000	psia	2.6	X	
GR1102P	B He tank press	0	3500	psia	1/1	L/H	2.0	0	4000	psia	2.6	X	
GR1201P	A He regulator press	0	350	psia	1/1	L/H	2.0	0	400	psia	2.6	X	
GR1202P	B He regulator press	0	350	psia	1/1	L/H	2.0	0	400	psia	2.6	X	
GR2121T	A fuel tank temp	20	120	°F	1/1	L/H	2.8	20	120	°F	3.4	X	
GR2122T	B fuel tank temp	20	120	°F	1/1	L/H	2.8	20	120	°F	3.4	X	
GR2201P	A fuel manifold press	0	350	psia	1/200	L/H	1.9	0	400	psia	2.6	X	
GR2202P	B fuel manifold press	0	350	psia	1/200	L/H	1.9	0	400	psia	2.6	X	
GR3201P	A oxid manifold press	0	350	psia	1/200	L/H	1.9	0	400	psia	2.6	X	
GR3202P	B oxid manifold press	0	350	psia	1/200	L/H	1.9	0	400	psia	2.6	X	
GR5031X	TCP switch B4U	1 = on			200	E,H						X	
GR5032X	TCP switch A4D	1 = on			200	E,H						X	
GR5033X	TCP switch B4F	1 = on			200	E,H						X	
GR5034X	TCP switch A4R	1 = on			200	E,H						X	
GR5035X	TCP switch A3U	1 = on			200	E,H						X	
GR5036X	TCP switch B3D	1 = on			200	E,H						X	
GR5037X	TCP switch B3A	1 = on			200	E,H						X	
GR5038X	TCP switch A3R	1 = on			200	E,H						X	
GR5039X	TCP switch B2U	1 = on			200	E,H						X	
GR5040X	TCP switch A2D	1 = on			200	E,H						X	
GR5041X	TCP switch A2A	1 = on			200	E,H						X	
GR5042X	TCP switch B2L	1 = on			200	E,H						X	
GR5043X	TCP switch A1U	1 = on			200	E,H						X	
GR5044X	TCP switch B1D	1 = on			200	E,H						X	
GR5045X	TCP switch A1F	1 = on			200	E,H						X	
GR5046X	TCP switch B1L	1 = on			200	E,H						X	
GR6001T	Quad 4 temp	20	200	°F	1/1	L/H	2.2	-100	200	°F	2.4	X	
GR6002T	Quad 3 temp	20	200	°F	1/1	L/H	2.2	-100	200	°F	2.4	X	
GR6003T	Quad 2 temp	20	200	°F	1/1	L/H	2.2	-100	200	°F	2.4	X	
GR6004T	Quad 1 temp	20	200	°F	1/1	L/H	2.2	-100	200	°F	2.4	X	
GR9609U	RCS main A closed	1 = closed			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9610U	RCS main B closed	1 = closed			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9613U	A/B crossfeed open	1 = open			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9631U	Ascent feed A fuel open	1 = open			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9632U	Ascent feed B fuel open	1 = open			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9641U	Ascent feed A oxid open	1 = open			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	
GR9642U	Ascent feed B oxid open	1 = open			1/1	E, L/H		Panel monitor (G = open, BP = closed)				X	

TABLE III.- LUNAR MODULE RCS MEASUREMENT LIST - Concluded

Measurement no.	Description	Telemetry data						Onboard display				Operational	DFI
		Low	High	Units	Sample rate, Hz	Type recording	RSS accuracy, percent	Low	High	Units	RSS accuracy, percent		
GR9661U	A4 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9662U	B4 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9663U	A3 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9664U	B3 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9665U	A2 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9666U	B2 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9667U	A1 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR9668U	B1 isolation valves closed	1 = closed			1	E, H		Panel monitor (G = open, BP = closed)				X	
GR4322T	TCA fuel inlet pair 4B temp	20	120	°F	1.25		2.4						X
GR4323T	TCA fuel inlet pair 3A temp	20	120	°F	10		2.4						X
GR4326T	TCA fuel inlet pair 2B temp	20	120	°F	10		2.4						X
GR4327T	TCA fuel inlet pair 1A temp	20	120	°F	10		2.4						X
GR4424T	TCA oxid inlet pair 3B temp	20	120	°F	1.25		2.4						X
GR4435T	3S oxid valve temp	0	200	°F	1.25		2.4						X
GR4441T	TCA fuel valve inlet 4D temp	0	200	°F	1.25		2.4						X
GR4448T	TCA fuel valve inlet 1D temp	0	200	°F	1.25		2.4						X
GR4570T	4D injector head temp	0	500	°F	10		2.3						X
GR4571T	4F injector head temp	0	500	°F	10		2.3						X
GR4573T	3U injector head temp	0	500	°F	10		2.3						X
GR4574T	3D injector head temp	0	500	°F	1.25		2.3						X
GR4577T	2U injector head temp	0	500	°F	10		2.3						X
GR4578T	2D injector head temp	0	500	°F	10		2.3						X
GR4582T	1D injector head temp	0	500	°F	10		2.3						X
GR4583T	1F injector head temp	0	500	°F	10		2.3						X

NOTE: H = High bit rate
L = Low bit rate
E = Event
G = Gray
BP = Barberpole

TABLE IV.- LUNAR MODULE RCS CAUTION AND WARNING LIMITS

Measurement no.	Description	Theoretical CW limits		Actual CW limits		Indicator lights
		Low	High	Low	High	
GR1101P	A He tank pressure	1696 psia		1696.8 psia		RCS caution
GR1102P	B He tank pressure	1696 psia		1692.6 psia		RCS caution
GR1201P	A He regulator pressure	164.4 psia	204.3 psia	164.2 psia	204.8 psia	RCS A reg. warning
GR1202P	B He regulator pressure	164.4 psia	204.3 psia	164.6 psia	205.3 psia	RCS B reg. warning
GR6001T	Quad 4 temperature	119° F	190° F	116.8° F	191.7° F	Heater caution
GR6002T	Quad 3 temperature	119° F	190° F	116.8° F	190.3° F	Heater caution
GR6003T	Quad 2 temperature	119° F	190° F	117.3° F	190.1° F	Heater caution
GR6004T	Quad 1 temperature	119° F	190° F	117.5° F	190.7° F	Heater caution
GR5031X to GR5046X	Thrust chamber pressure switches[a]					RCS TCA warning and red quad flag

[a]TCA failure detection system - signals engine "on" or "off" failure subject to following logic:

1. Off failure - One on-command greater than 80 msec or six consecutive on-commands of less than 80 msec with no corresponding TCP switch response signal a TCA failure (failure signaled on 7th pulse).

2. On failure - Opposing engine on-commands combinations, in the table shown to the right, signal a TCA failure.

THRUSTER FAILED ON	ON COMMAND SIGNALS															
	A1U	B1D	A1F	B1L	B2U	A2D	A2A	B2L	A3U	B3D	B3A	A3R	B4U	A4D	B4F	A4R
A1U	●	●							●							
B1D	●	●								●						
A1F			●				●								●	
B1L				●				●								●
B2U					●	●							●			
A2D					●	●								●		
A2A			●				●				●					
B2L				●				●				●				
A3U	●								●	●						
B3D		●							●	●						
B3A							●				●				●	
A3R								●				●				●
B4U					●								●	●		
A4D						●							●	●		
B4F			●								●				●	
A4R				●								●				●

TABLE V.- PROPELLANT SERVICING DATA

Parameter	System A fuel	System A oxidizer	System B fuel	System B oxidizer
Required load, lb	107.7 ± 0.9	208.8 ± 1.9	107.7 ± 0.9	208.8 ± 1.9
Ullage requirement, in^3	117 ± 6	231.5 ± 6	117 ± 6	231.5 ± 6
Actual load, lb	107.7	208.8	107.7	208.8
Actual ullage, in^3	117	231.5	117	231.5
Trapped in manifolds, lb . . .	5.3 to 5.4	8.5 to 8.8	5.3 to 5.4	8.5 to 8.8
Trapped in tanks	1.0 to 2.1	2.0 to 4.0	1.0 to 2.1	2.0 to 4.0
Nominal deliverable[a]	100.8	197.1	100.8	197.1

[a]The O/F ratio uncertainty not included.

TABLE VI.- LUNAR MODULE RCS PRELAUNCH PRESSURE HISTORY

Date	Eastern standard time	A helium tank pressure, psia	B helium tank pressure, psia	A regulator pressure, psia	B regulator pressure, psia	A fuel tank temp-erature, °F	B fuel tank temp-erature, °F	A fuel manifold pressure, psia	A oxid manifold pressure, psia	B fuel manifold pressure, psia	B oxid manifold pressure, psia	Remarks
2-01-69	0230							2.8	1.4	1.4	1.4	Manifold evacuation
2-12-69	1600			11.1	15.2			2.8	1.4	1.4	1.4	
2-14-69	1330			12.5	16.6			2.8	1.4	1.4	1.4	
2-19-69	1800							2.8	1.4	1.4	1.4	
2-23-69	≈2000							43	41	45	43	Interconnects open and MSOV's closed
2-23-69	2000							51.2	52.6	48.4	54.0	Interconnects closed and MSOV's open
2-24-69				15.2	19.4	71	70.6	51.2	52.6	48.4	54.0	
2-26-69	1230	2988	2947	16.6	19.4	70.2	69.0	51.2	52.6	48.4	54.0	Helium loaded at 2000 hr on 2-24-69
2-26-69	2100	2974	2947	16.6	19.4	69.8	69.0	38.7	45.7	36.0	45.7	Isolation valves opened at 2000 hr on 2-26-69
2-27-69	1130	3002	2960	16.6	20.8	71.8	71.4	40.1	49.8	37.4	49.8	
2-27-69	1630	3002	2960	16.6	20.8	71.8	71.4	40.1	48.4	37.4	48.4	
2-28-69	1000	3002	2974	16.6	20.8	73.0	72.6	41.5	51.2	37.4	51.2	
3-03-69	0125	2974	2947	18.0	21.0	69.0	68.0	40.0	48.0	37.0	49.0	
3-03-69	1001	2988	2947	18.0	21.0	69.0	69.0	40.0	48.0	37.0	49.0	

TABLE VII.- FLIGHT TIME LINE

Event	Start, g.e.t.	End, g.e.t.	Duration, sec
Lift-off (16:00:00.7 G.m.t.)	00:00:00.7		
RCS pressurization	47:36:58		
RCS hotfire	48:04:36		
DPS-1 ullage (2 engine-B)	49:41:25.6	49:41:35.2	9.6
DPS-1 burn	49:41:34	49:47:44	370.0
RCS hotfire	91:19:17		
LM/CSM undocking	92:39:36		
DPS phasing ullage (2 engine-B)	93:47:28.0	93:47:36.3	8.3
DPS phasing maneuver	93:47:35.4	93:47:54.0	18.6
DPS insertion ullage (2 engine-B)	95:39:01.0	95:39:09.5	8.5
DPS insertion maneuver	95:39:08.4	95:39:31.4	23.0
LM staging maneuver (RCS 4 engine)	96:16:06.5	96:16:38.2	31.7
CDH ullage (4 engine)	[a]96:58:12	[a]96:58:16	4.0
CDH maneuver	[a]96:58:15.0	[a]96:58:17.9	2.9
Terminal phase initiation (2 engine-Z axis)	[a]97:58:00.0	[a]97:58:34.7	34.7
LM CSM docking no. 2	99:02:26		
LM undocking from CSM	[a]101:22:45		
APS burn to depletion ullage (2 engine-B)	101:52:41.8	101:53:15.9	34.1
APS burn to depletion	101:53:15.4	101:59:05.4	350.0
CM landing	241:00:54		

[a]Time unverified by reduced data.

TABLE VIII.- LUNAR MODULE RCS ΔV PERFORMANCE

Event	Time, g.e.t.	Engine	Firing duration, sec	Vehicle weight, lb	ΔV expected, ft/sec (a)	ΔV actual from PIPA, ft/sec (b)	Average effective thrust (min. and max. value, lb) (b)
DPS-1 ullage	49:41:25.63	1, 3 down	9.60	62 509	0.90	0.79 to 0.94	[e]79.6 to 95.4
DPS phasing ullage	93:47:27.97	1, 3 down	8.35	22 185	2.01	Noisy data	-
DPS insertion ullage	95:39:01.03	1, 3 down	8.50	21 859	2.26	[d]1.84 to 1.99	[e]68.0 to 98.0
LM staging	96:16:06.54	1, 2, 3, 4 down	31.70	10 133	40.46	39.2 to 39.9	100.2 to 102.6
CDH ullage[c]	96:58:12	1, 2, 3, 4 down	4.0	10 032	5.1	-	-
TPI[c]	97:58:00	Either 1, 4 forward or 2, 3 aft	34.7	9 948	44.4	-	-
APS burn to depletion ullage	101:52:41.78	1, 3 down	34.1	9 518	23.19	22.95 to 23.55	103.9 to 105.2

[a]Based on expected effective thrust and firing duration corrected for attitude control.

[b]Maximum and minimum thrust value stated because PIPA data are printed out every 2 seconds in whole numbers only, then rezeroed, thus fractional counts are lost.

[c]Firing performed between stations; therefore, the expected ΔV is only an estimate and the actual ΔV was not available.

[d]PIPA data indicated unusual decrease through the five data points.

[e]Effective thrust with unstaged vehicle because of plume impingement is predicted to be 92.0 lb for engines 1, 3, and 4 down, and 62.8 lb for engine 2 down.

TABLE IX.- LUNAR MODULE RCS PROPELLANT CONSUMPTION SUMMARY

[O/F ratio assumed to be 1.92]

Parameter	Fuel, lb	Oxidizer, lb
Loaded		
System A	108	209
System B	108	209
Consumed from RCS supply		
System A	73 [a](76)	140 (147)
System B	48 (50)	92 (95)
Remaining at last data transmission		
System A	35 (32)	69 (62)
System B	60 (58)	117 (114)

[a]Numbers without parentheses are PQMD results. Numbers enclosed in parentheses are ground calculated PVT results.

NOTE: A portion of the RCS propellants was supplied from the APS tanks during LM staging and the APS burn to depletion. The APS propellant was used by both system A and system B during 21 seconds of the staging maneuver and by system B only during the APS burn to depletion. A summary of RCS propellant usage from the APS tanks is as follows:

	Oxidizer, lb	Fuel, lb	Total, lb[b]
LM staging	20.1	9.9	30.0
Ullage	17.0	8.4	25.4
Burn to depletion	29.1	14.3	43.4
Totals	66.2	32.6	98.8

[b]Numbers are based on engine on-time and flow-rate data.

TABLE X.- LUNAR MODULE RCS PROPELLANT CONSUMPTION DURING MAJOR EVENTS

Event	Time, g.e.t.		PQMD results, lb				Ground calculated PVT results, lb			
	From	To	System A	System B	Total, A+B	Accumulated total	System A	System B	Total, A+B	Accumulated total
Inadvertent system A interconnect valve opening	47:39:35.1	47:39:38.4	(a)							
RCS hotfire no. 1	48:04:36	49:27:25	3.5	1.2	4.7	4.7	3.0	2.7	5.7	5.7
DPS-1 burn	49:27:25	50:00:00	5.3	14.1	19.4	24.1	4.0	13.7	17.7	23.4
RCS hotfire no. 2	91:17:28	92:03:55	2.6	2.7	5.3	29.4	3.1	3.1	6.2	29.6
LM/CSM undocking and formation flying	92:03:55	93:42:45	11.2	15.0	26.2	55.6	11.5	16.7	28.2	57.8
DPS phasing	93:42:45	94:06:41	6.5	13.8	20.3	75.9	8.7	13.7	22.4	80.2
Phasing to insertion	94:06:41	95:34:01	5.0	6.5	11.5	87.4	2.3	5.4	7.7	87.9
DPS insertion	95:34:01	96:04:00	3.8	10.0	13.8	101.2	5.5	11.0	16.5	104.4
LM staging	96:04:00	96:22:24	8.8	12.7	[b]21.5	122.7	8.3	13.2	[b]21.5	125.9
CDH maneuver	96:22:24	97:15:11	6.4	5.9	12.3	135.0	8.8	6.0	14.8	140.7
TPI maneuver	97:15:11	98:05:20	22.1	17.9	40.0	175.0	85.6 (TPI maneuver and TPI through docking)	59.9 (TPI maneuver and TPI through docking)	145.5 (TPI maneuver and TPI through docking)	
TPI through docking	98:05:20	101:00:00	58.8	40.6	99.4	274.4				286.2
APS burn to depletion	101:00:00	103:44:01	78.2	(c)	78.2	352.6	82.3	(c)	82.3	368.5
Totals			212.2	140.4		352.6	223.1	145.4		368.5

[a]An inadvertent system A interconnect valve opening allowed approximately 5.0 lb of RCS propellant to flow into the APS system.

[b]During LM staging, the interconnect valves were opened on both systems A and B for about 21 seconds. This resulted in 30 lb usage from the APS system.

[c]System B was used in the interconnect mode during the APS burn to depletion. This resulted in 68.8 lb usage from the APS.

NOTE: The ground calculated PVT data are not considered as accurate as the PQMD data for the short time periods above. The table values represent the total quantity of propellant consumed during the time interval shown, not just during the event listed.

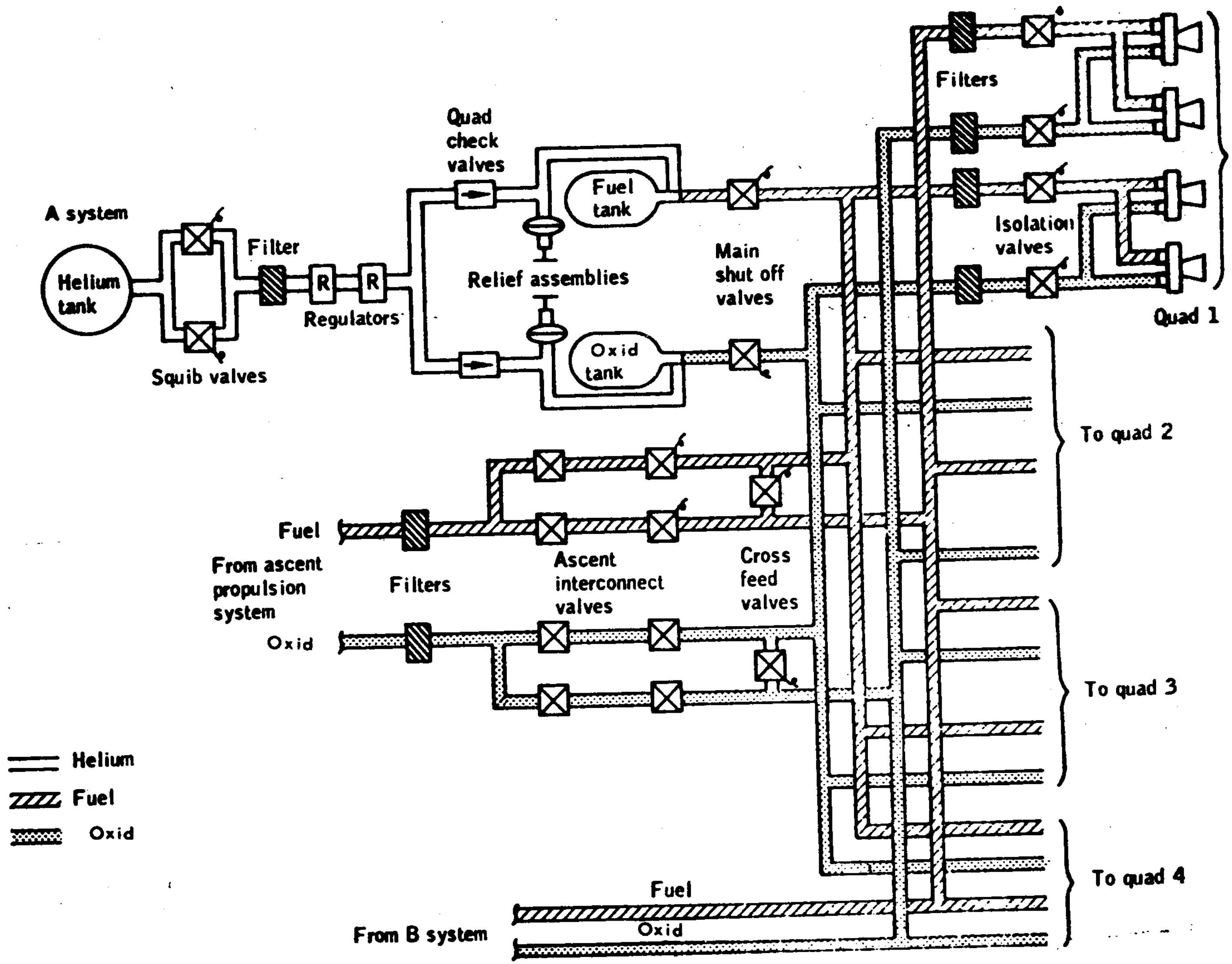


Figure 1.- Lunar module RCS simplified schematic.

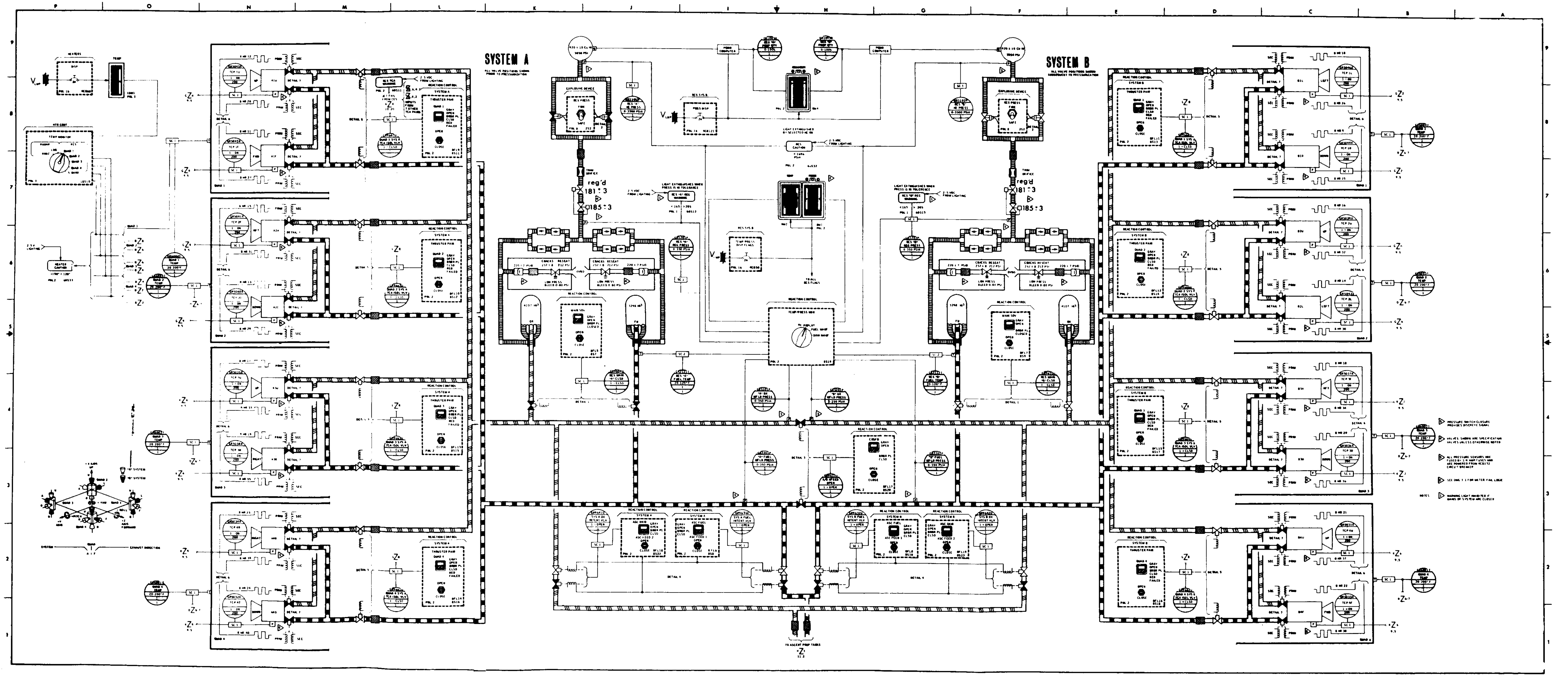


Figure 2.- Lunar module RCS mechanical schematic.

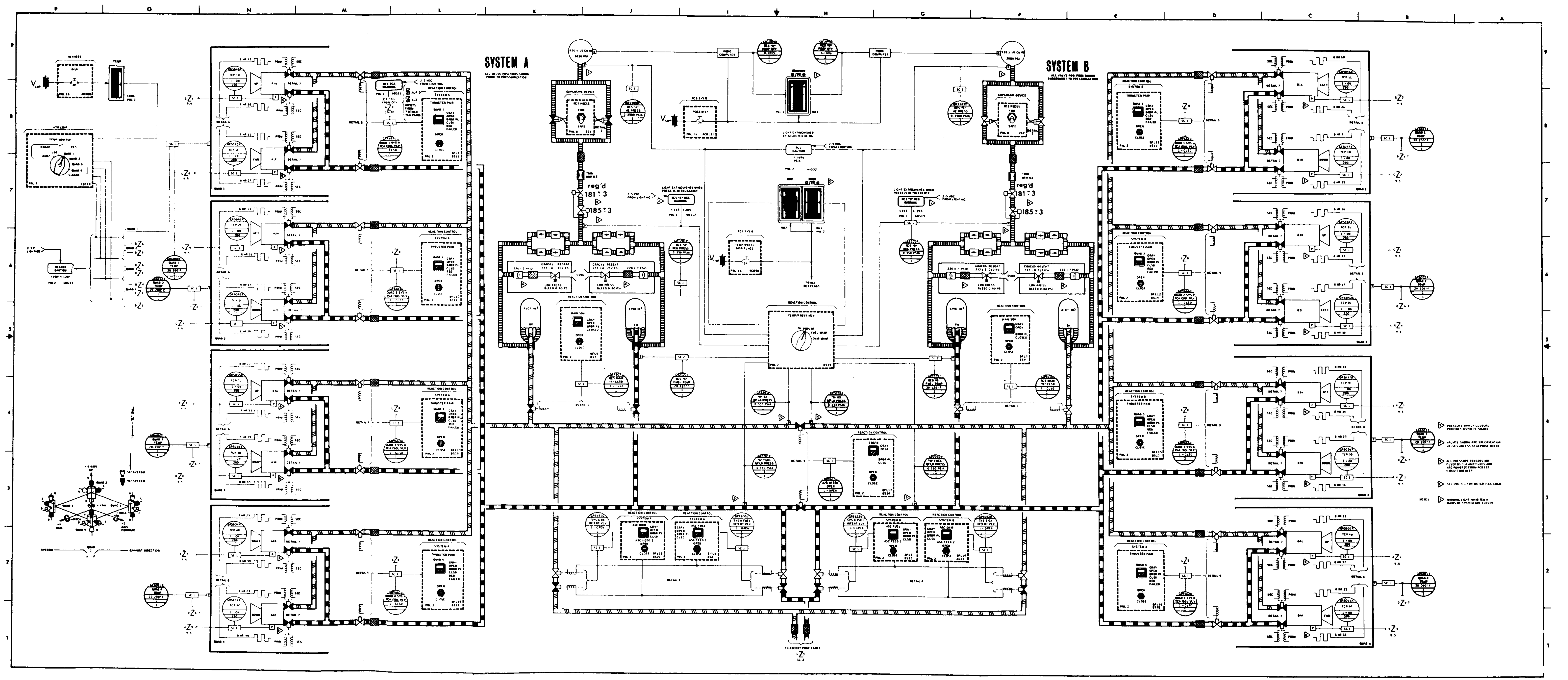


Figure 2.- Lunar module RCS mechanical schematic.

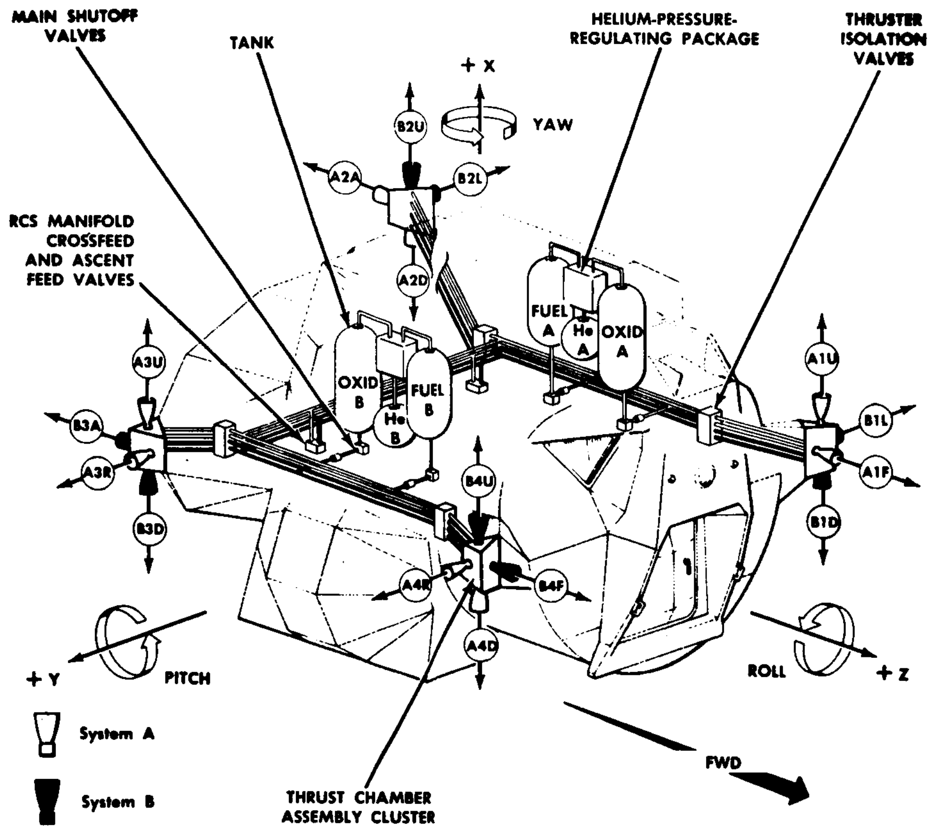


Figure 3.- Lunar module RCS component locations.

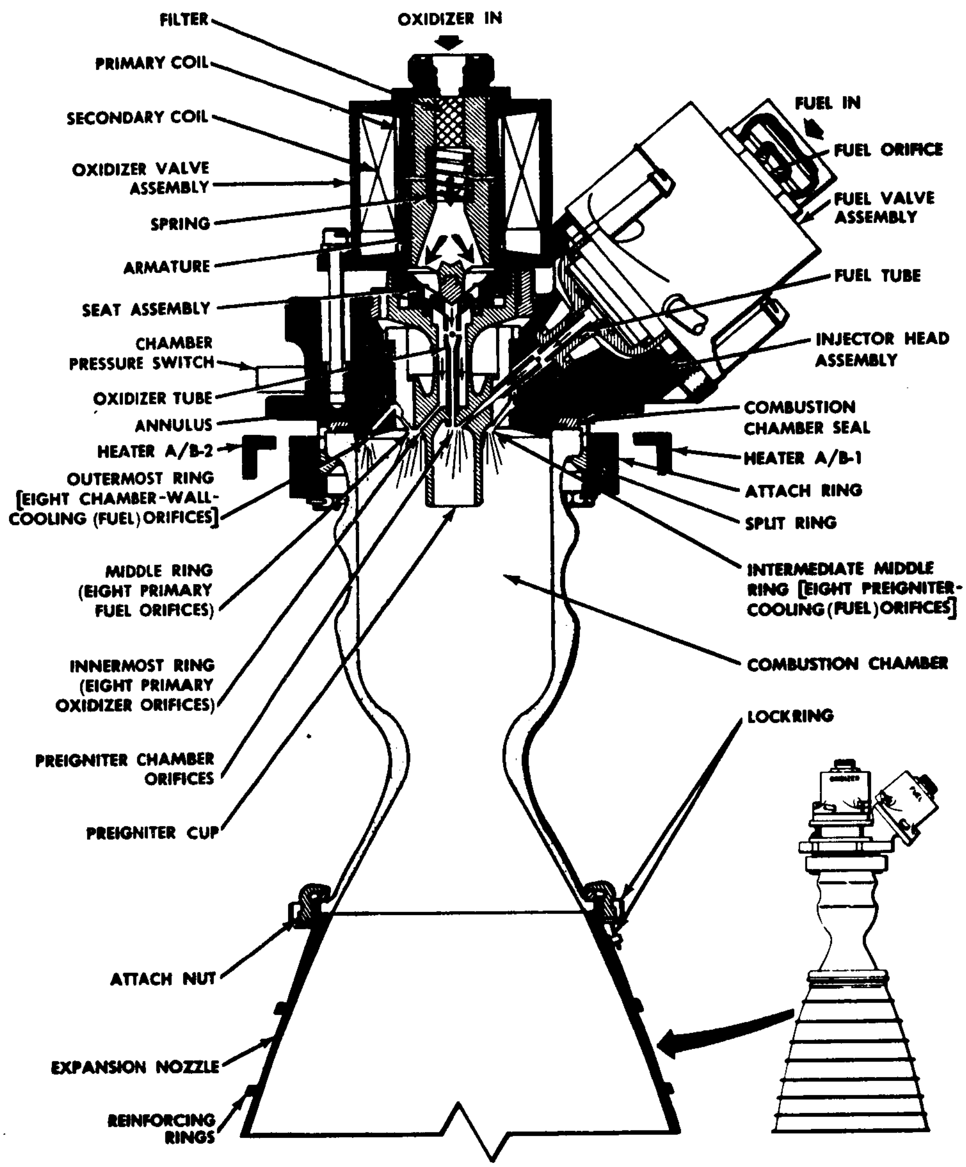
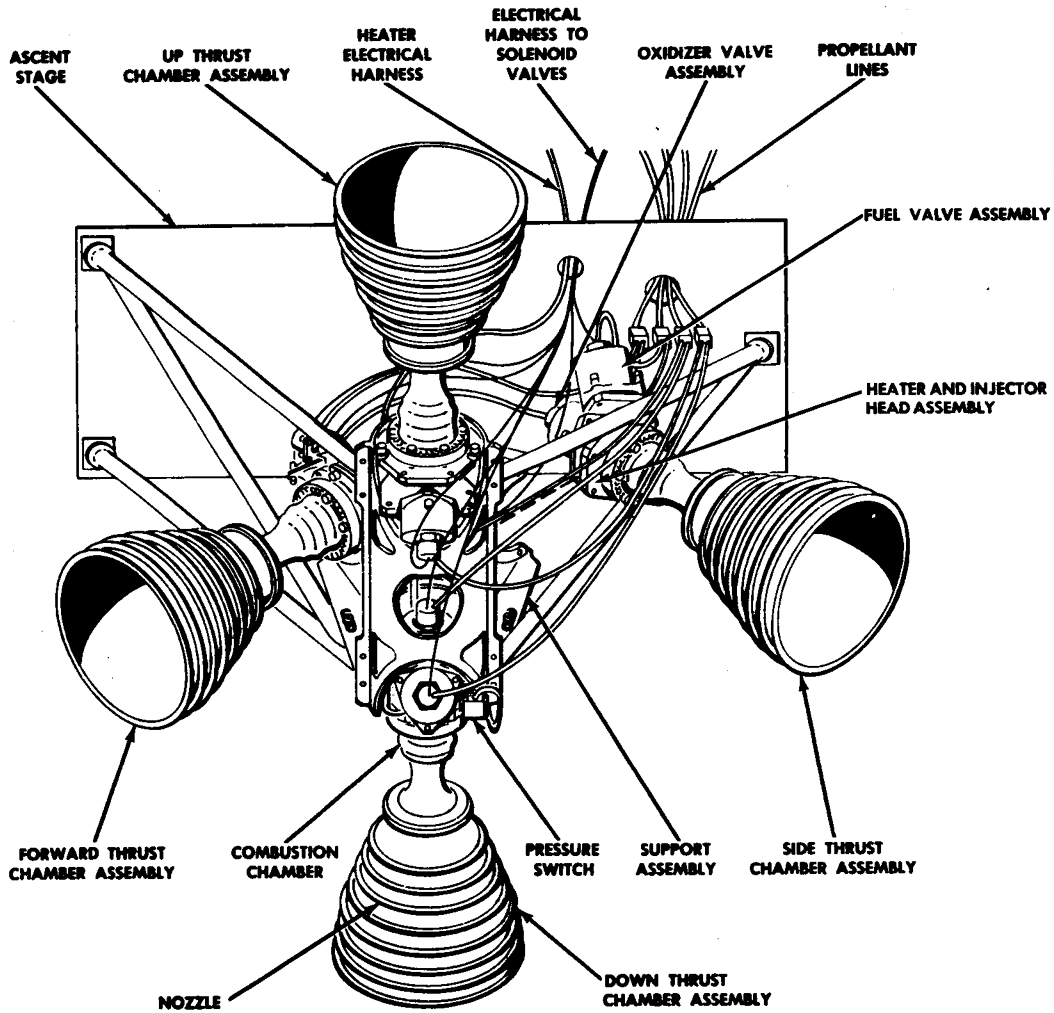


Figure 4.- Thrust chamber assembly (engine).



Note:
The cluster is shown with the thermal shield removed.

Figure 5.- Thrust chamber assembly cluster (quad).

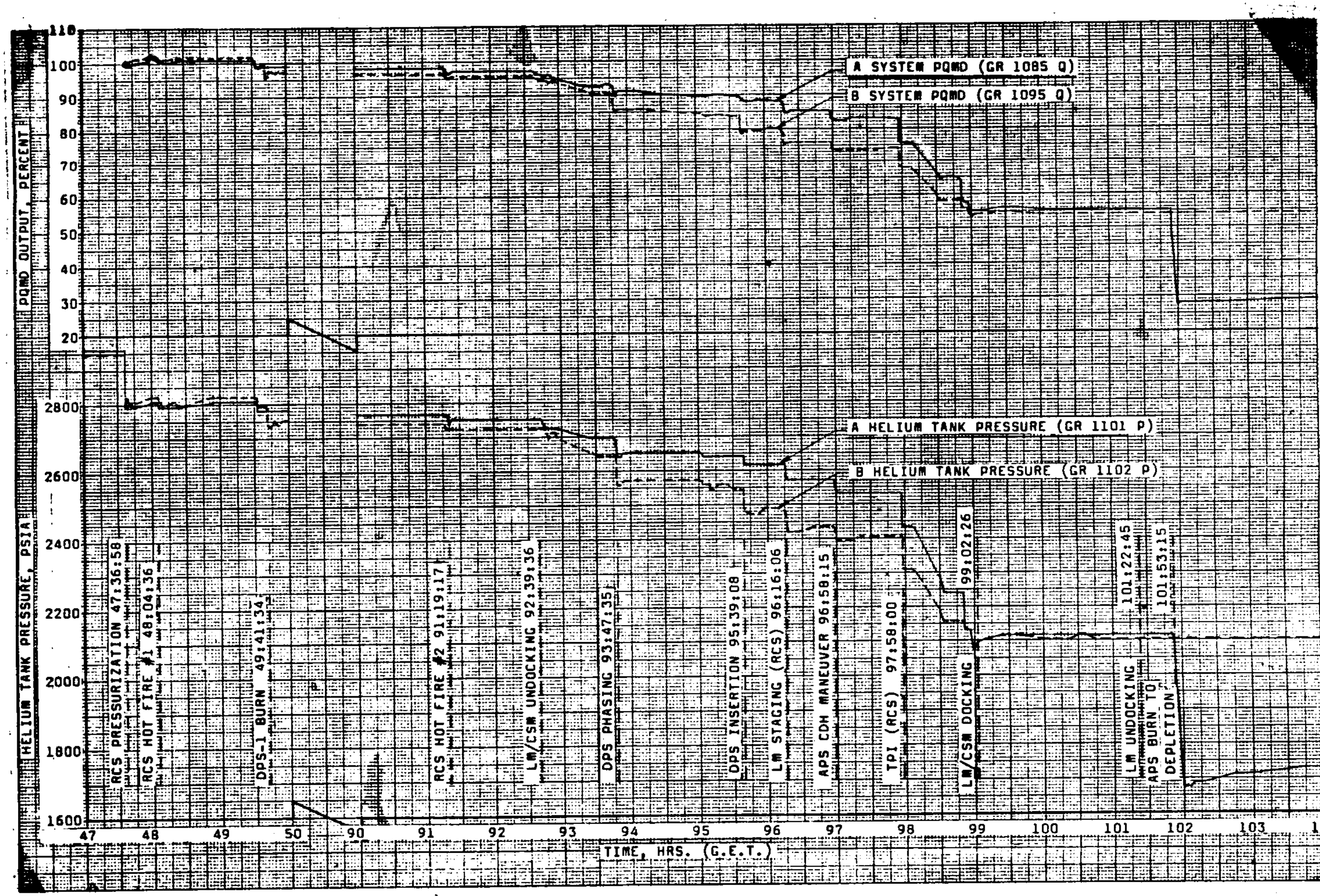


Figure 6.- Lunar module RCS PQMD and helium tank pressure profiles.

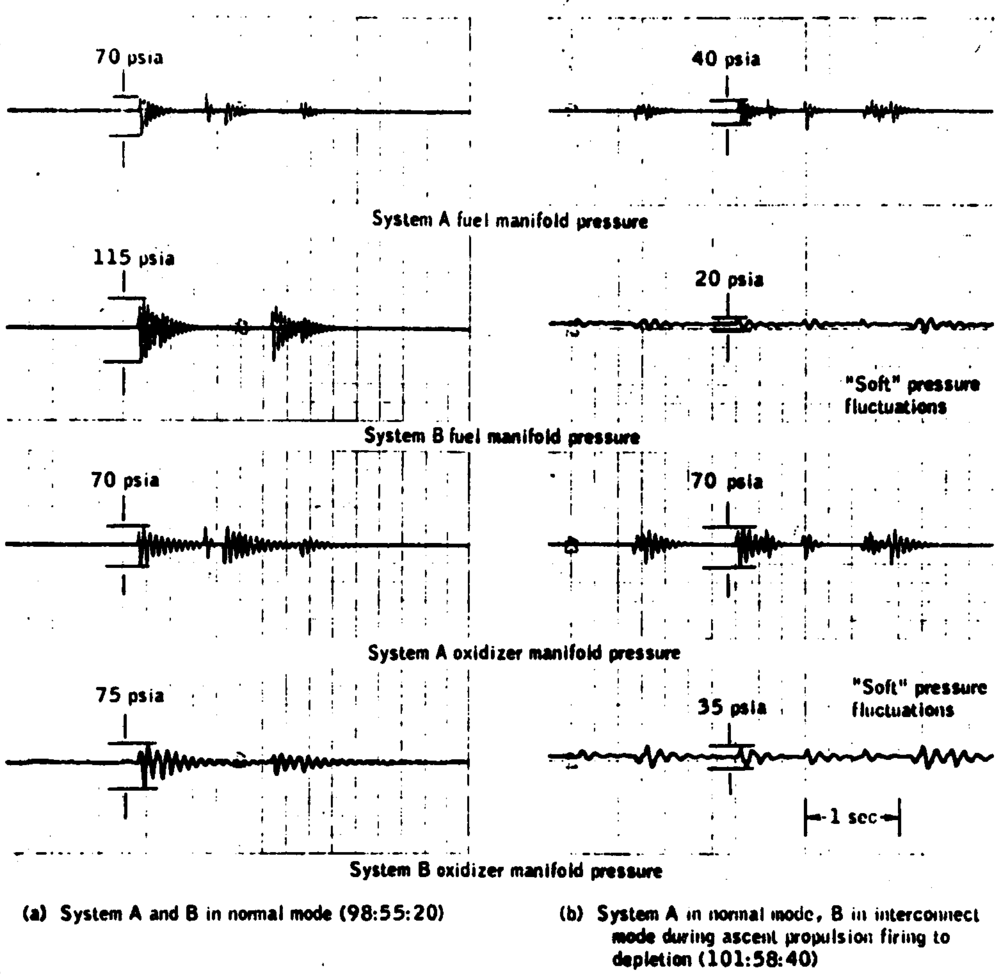


Figure 7.- Manifold pressures for normal-mode operation and during ascent propulsion firing to depletion.

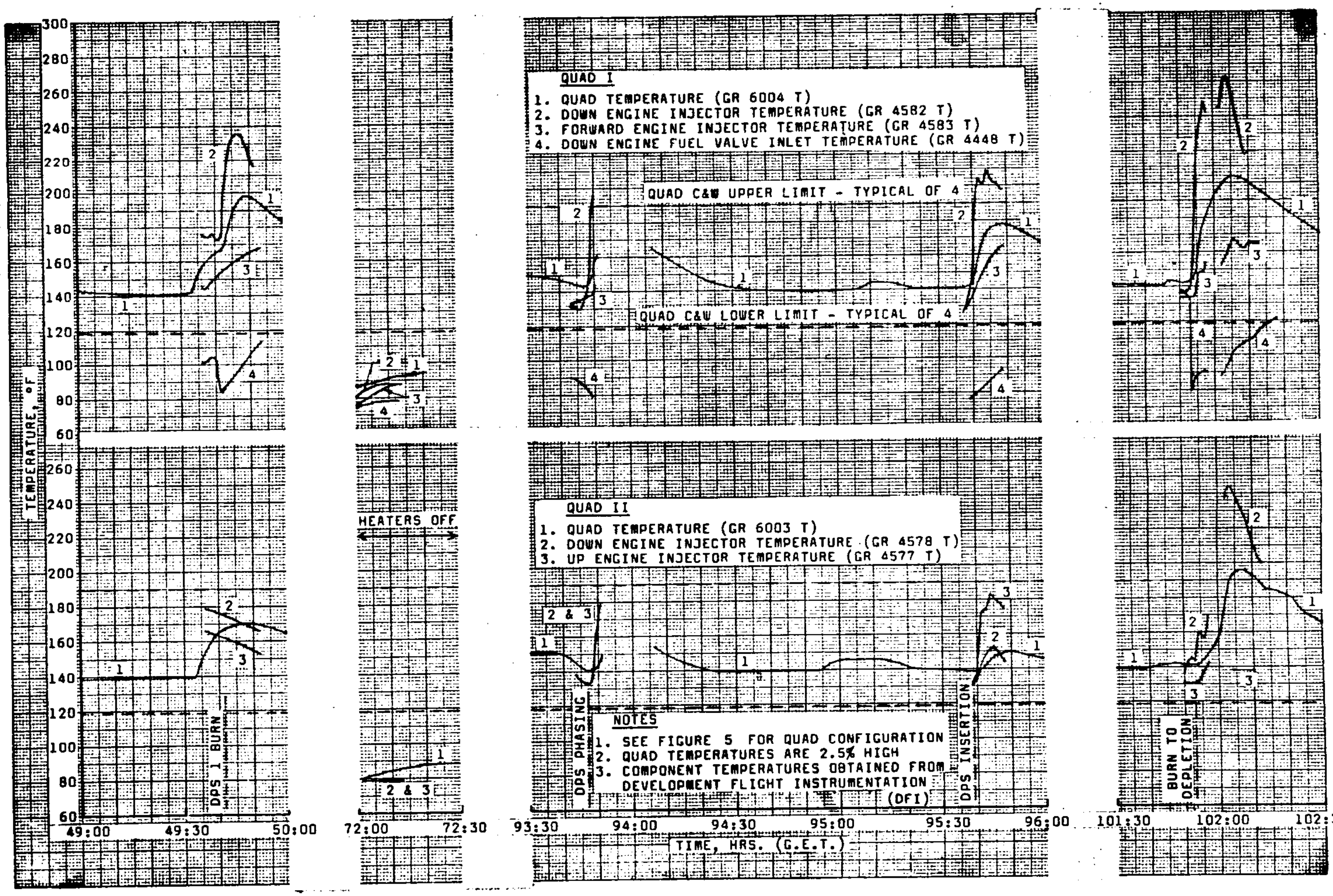


Figure 8.- Comparison of quad temperatures with engine component temperatures.

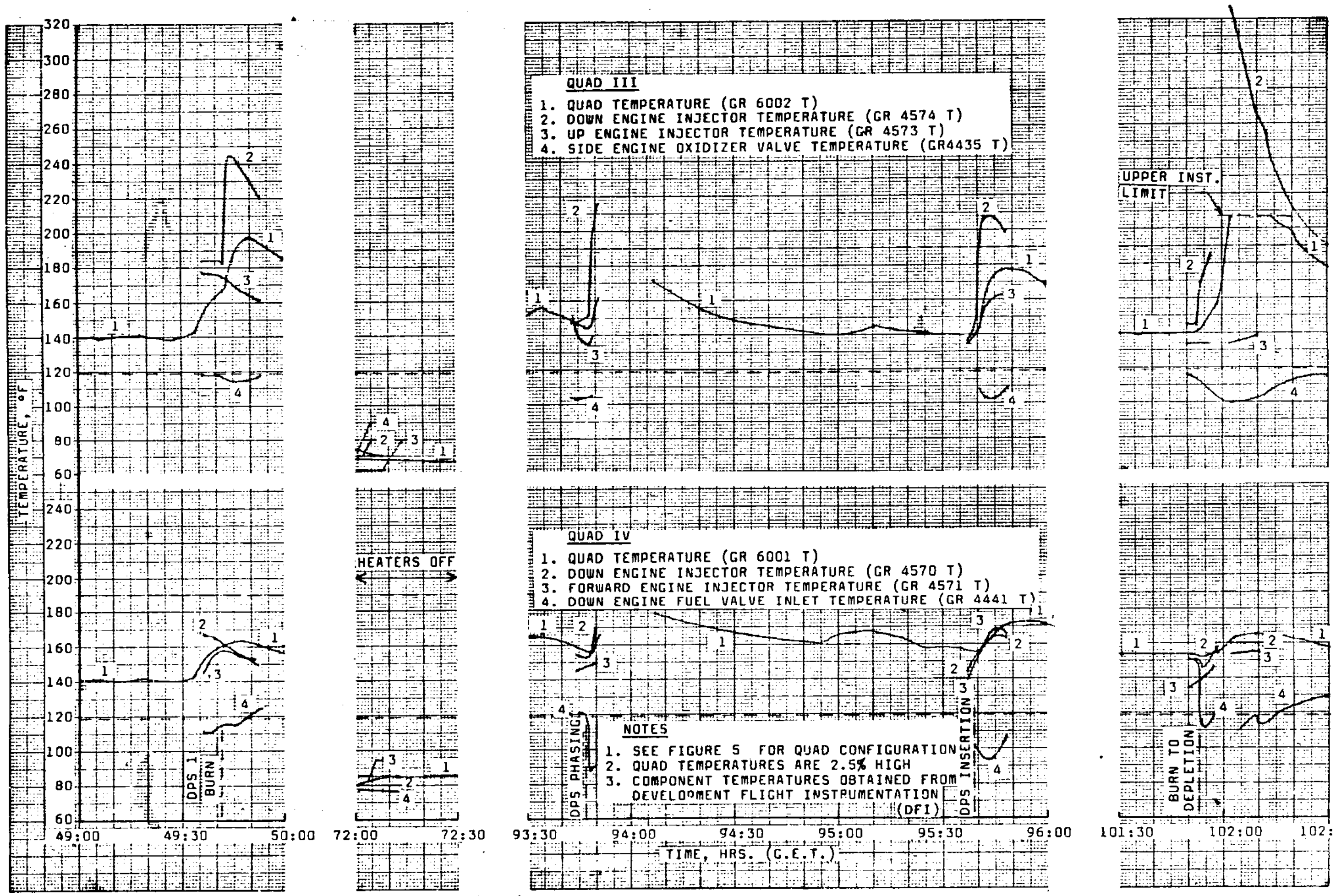
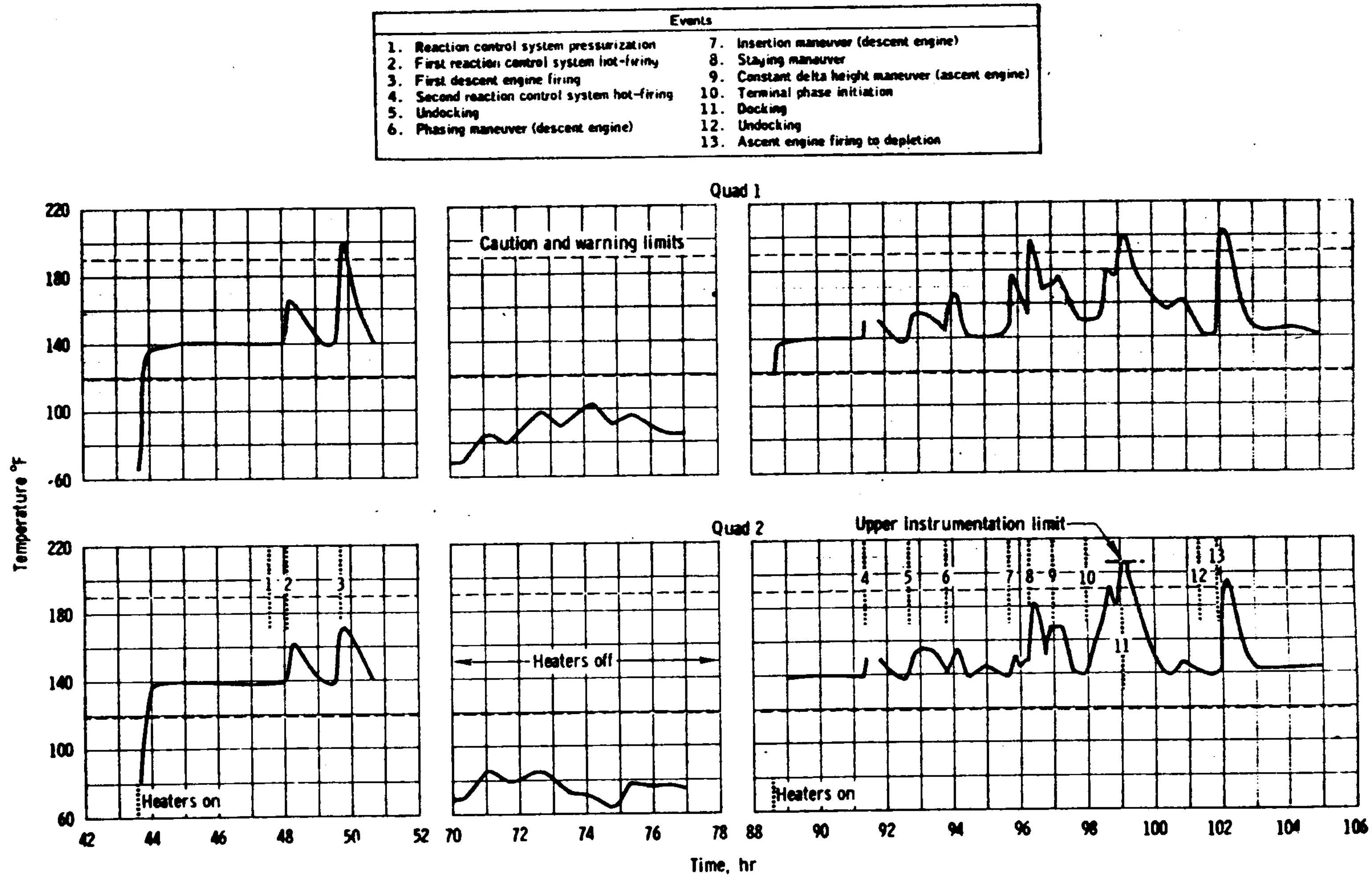
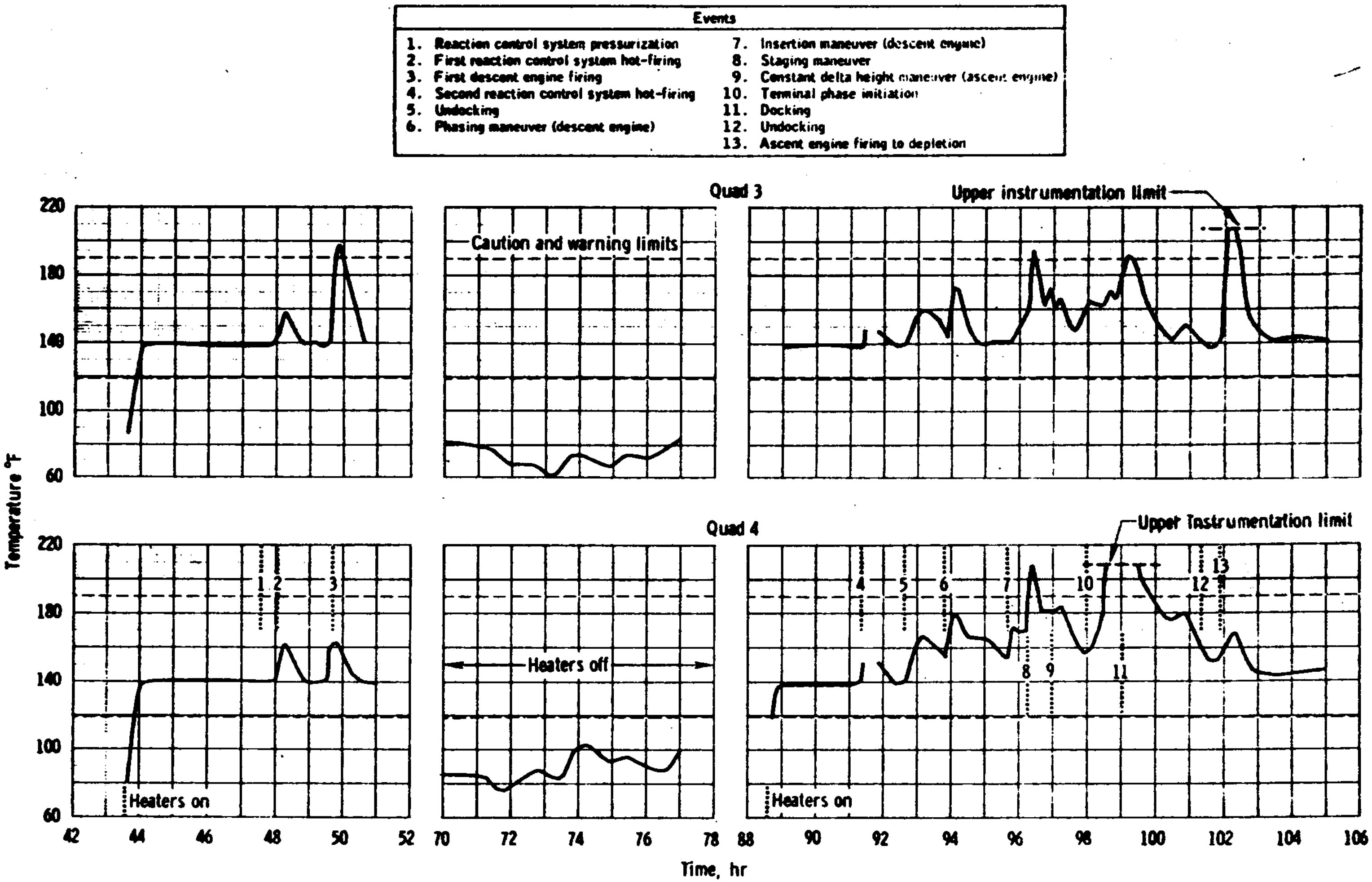


Figure 8.- Concluded.



NOTE: Quad temperatures shown are about 2.5 percent high because of a calibration error.

Figure 9.- Reaction control system quads 1 and 2 temperature histories.



NOTE: Quad temperatures shown are about 2.5 percent high because of a calibration error.

Figure 10.- Reaction control system quads 3 and 4 temperature histories.

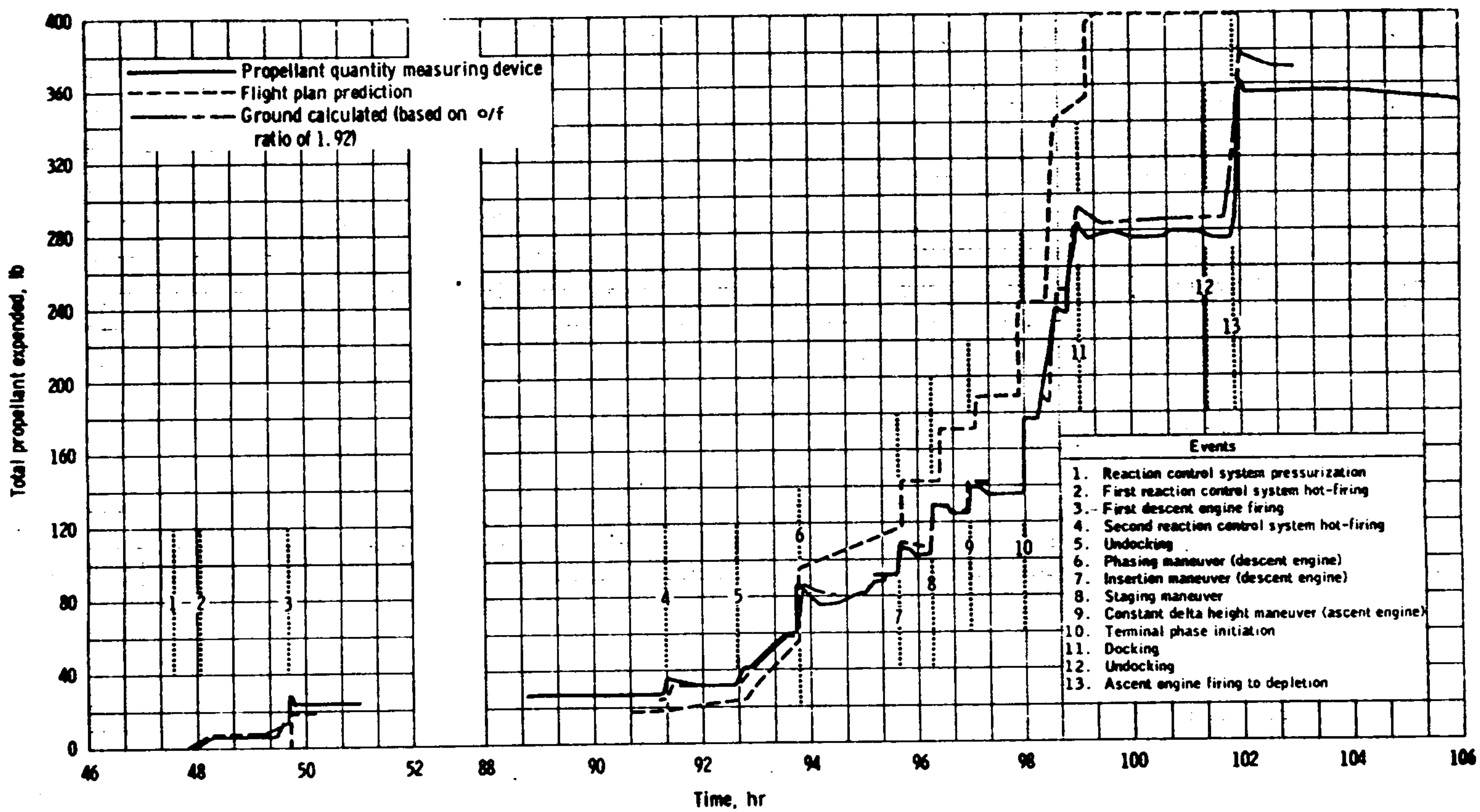


Figure 11.- Comparison of predicted and actual propellant comsumption.

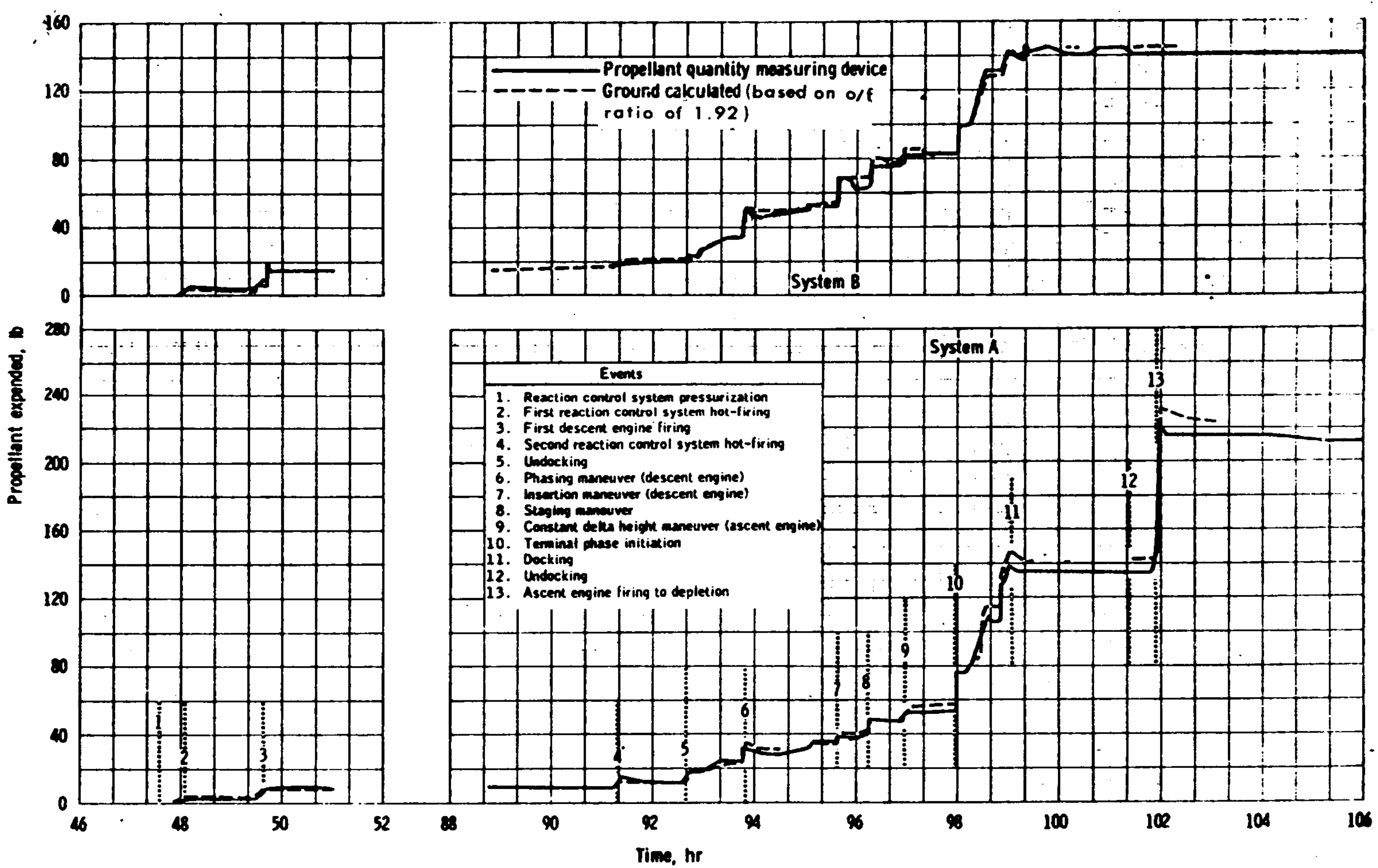


Figure 12.- Propellant usage from systems A and B.

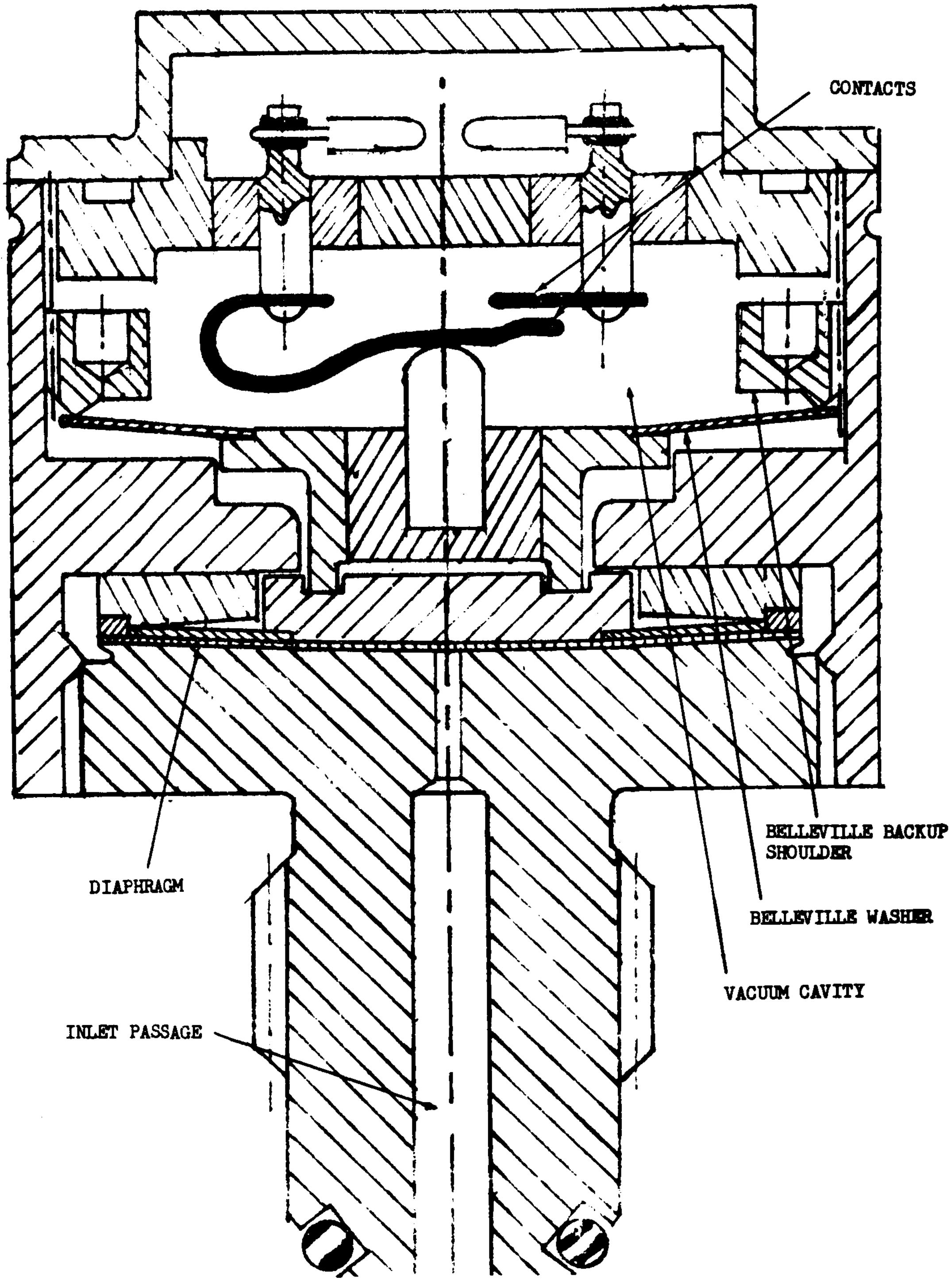


Figure 13.- Pressure switch assembly — LSC 310-651-5-1.